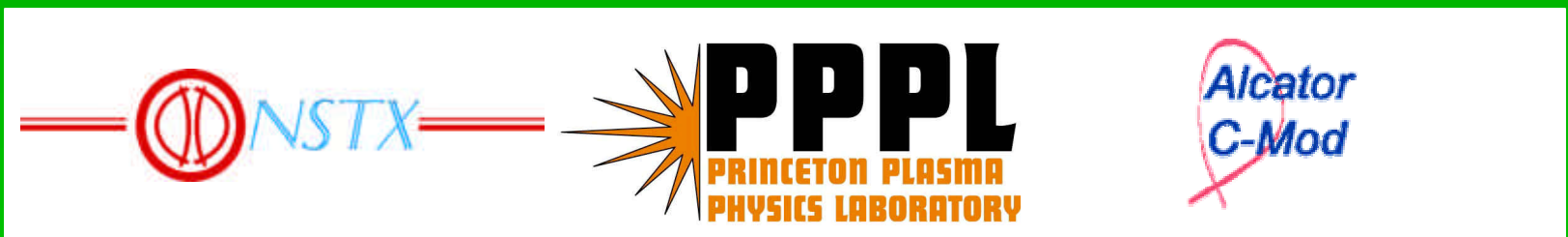


*US-Japan Workshop on Spatiotemporal Description of  
Edge Plasma Transport in Theory and Experiment  
September 6, 2003*

## **Analysis of GPI Data from NSTX and C-Mod**

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W. M. Nevins<sup>4</sup>, N. Pomphrey, D. Silver<sup>5</sup>,  
J. L. Terry<sup>6</sup>, X. Q. Xu<sup>4</sup>, S. J. Zweben**



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# Outline

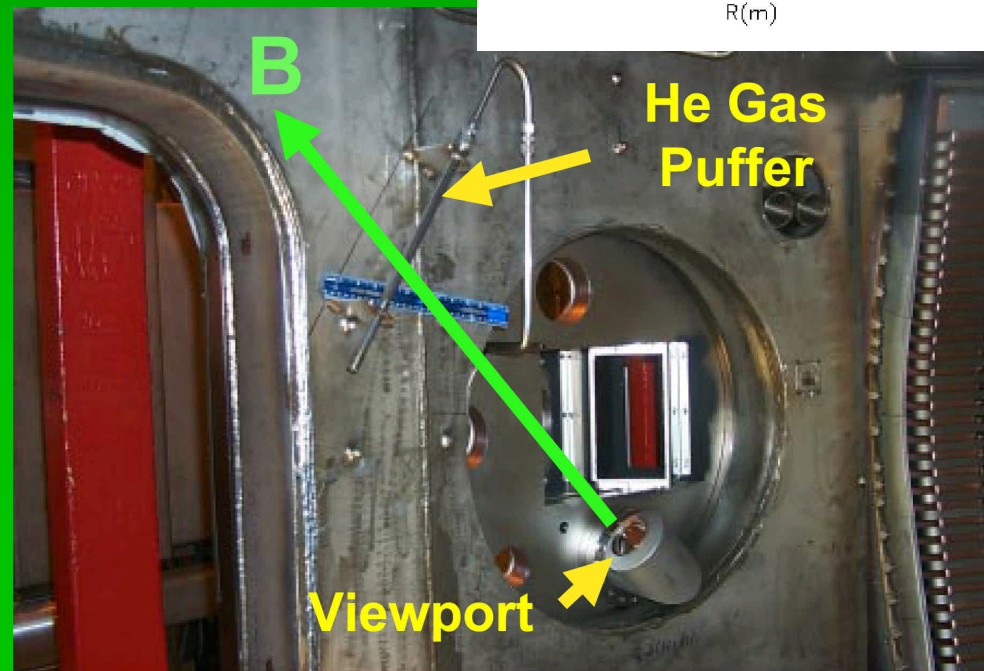
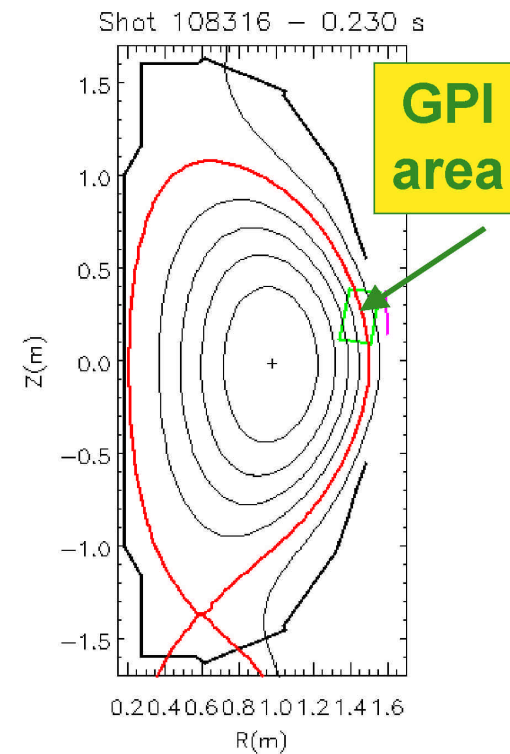
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- **Experiment**
  - Description of GPI diagnostic,
  - Movies from NSTX,
  - Turbulence characteristics,
  - Movies from C-Mod,
  - Compare C-Mod & NSTX turbulence.
- **Analysis & Theory**
  - NLET & BOUT  $k_{\text{pol}}$  comparison with C-Mod,
  - DEGAS 2 benchmark,
  - Use GPI data to infer 2-D  $n_e(x,y,t)$ ,
    - Apply to theory of blob motion.
  - Extract velocity field from GPI data,
  - Feature tracking,
  - 3-D visualization of GPI data,
  - Principal Component Analysis.

# Gas Puff Imaging (GPI) Experiments Designed to Measure 2-D Structure of Edge Turbulence

- Puff neutral gas near outer wall,
- View with fast camera fluctuating visible emission resulting from electron impact excitation of that gas,
- Use sightline || to B to see radial & poloidal structure,
  - Compare with turbulence measured by probes,
  - And with output from plasma turbulence codes.

NSTX Configuration



# GPI Diagnostic Interpretation

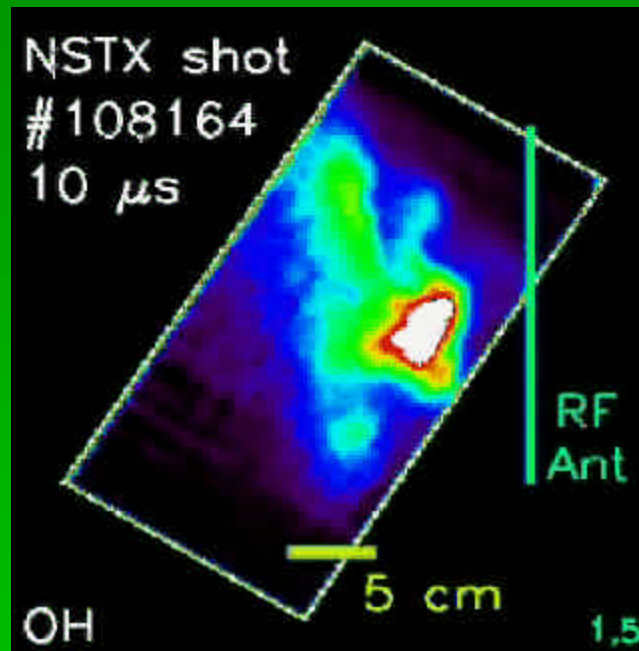
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- Hel / D<sub>a</sub> light emission “I” visible where  $5 \text{ eV} < T_e < 50 \text{ eV}$ ,
- $I \propto n_e^a T_e^b$  where  $a \gg 0.5$  (0.5) and  $b \gg 0.7$  (0.5) near center of cloud for Hel in NSTX (D<sub>2</sub> in C-Mod),
- Space-time structure of I similar to  $n_e^a$ ,
  - but  $dI/I \gg a \, dn_e/n_e$
- Fluctuation spectra of I similar to probe and reflectometer
- *GPI light gives approximate structure of edge turbulence*

# Composite NSTX GPI Movie

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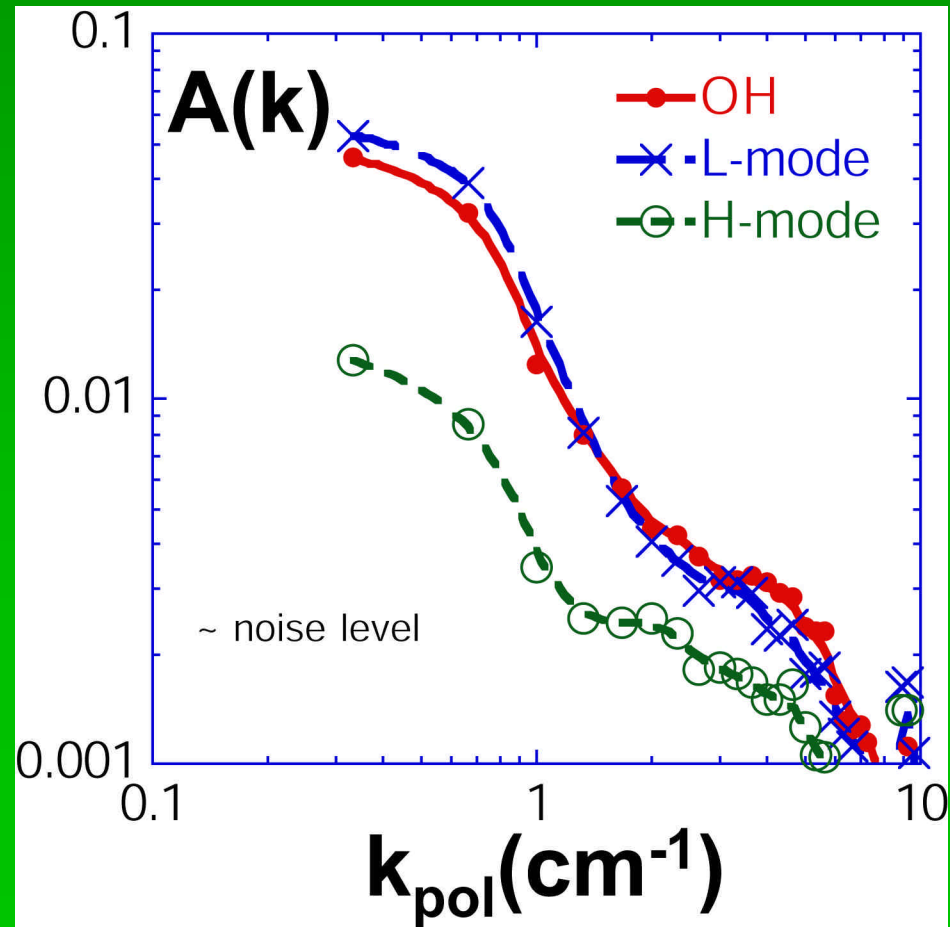
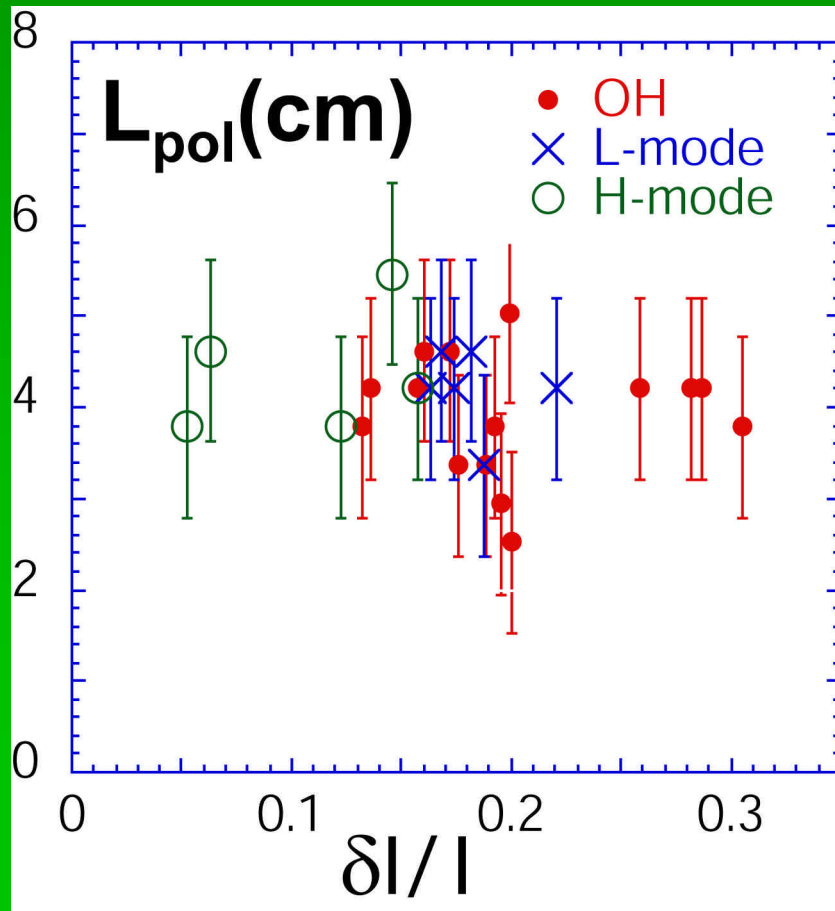
10  $\mu$ s / frame  
28 frames



For more NSTX & C-Mod GPI movies, see  
<http://www.pppl.gov/~szweben>

# Poloidal Correlation Length & k-Spectrum

- $L_{\text{pol}} \gg 4 \text{ cm}$  or  $k_{\text{pol}} r_s \gg 0.2$  (similar to other experiments)
- H-mode  $dI/I$  lower than L-mode (with much variation)



# Summary of NSTX Results So Far

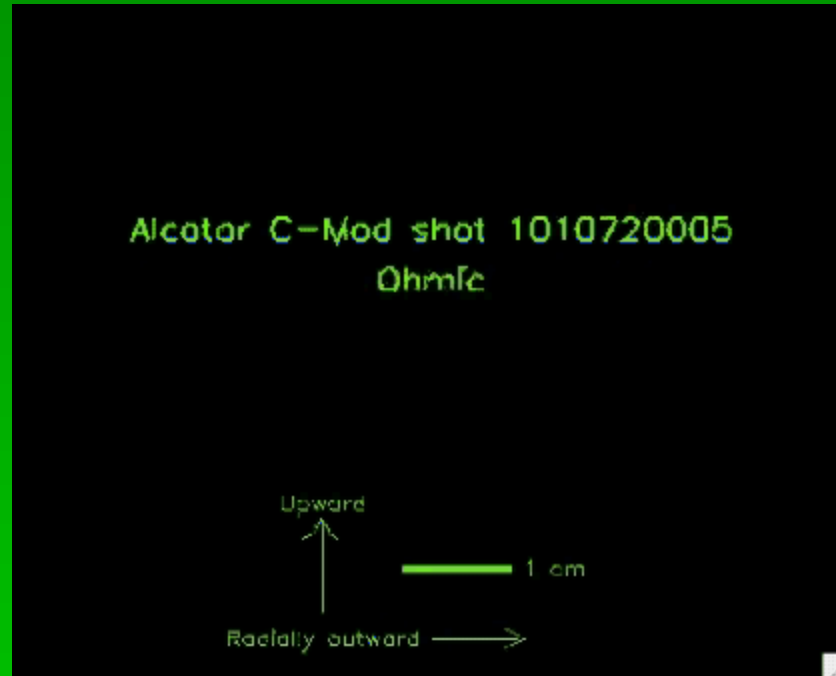
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- Images consistent with previous measurements
  - Large fluctuation level in edge
  - Broad frequency & k-spectrum
  - Approximately isotropic structure  $\wedge B$
- Coherent structures seem to move through edge
  - “Blob-like” look similar to DIII-D IPO’s
  - “Wave-like” look similar to EDA, QCM
- H-mode *generally* more quiescent than L-mode
  - Considerable variation in behavior
  - Transitions can happen very fast

# Composite Alcator C-Mod GPI Movie

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4  $\mu$ s / frame  
Separatrix = solid line  
Limiter = dashed lines  
Star = gas puff nozzle



For more NSTX & C-Mod GPI movies, see  
<http://www.pppl.gov/~szweben>



# NSTX & C-Mod GPI Turbulence Qualitatively Similar

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- Large, intermittent, transport events « blobs or filaments,
- Strong, non-Gaussian, SOL turbulence,
- Structures move poloidally & radially,
  - Speeds  $\approx 10^5$  cm/s.

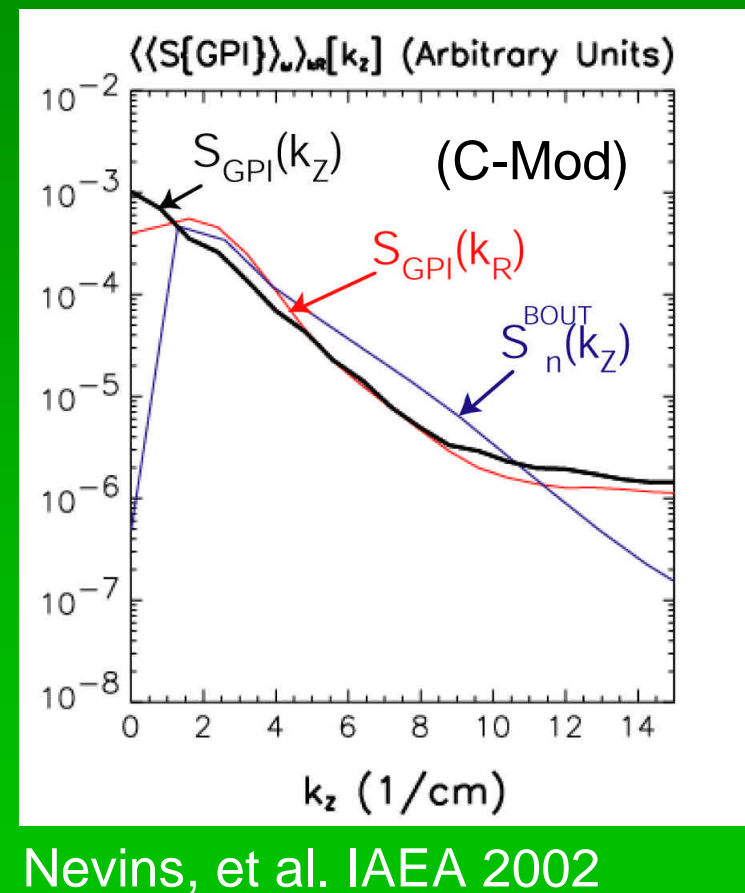
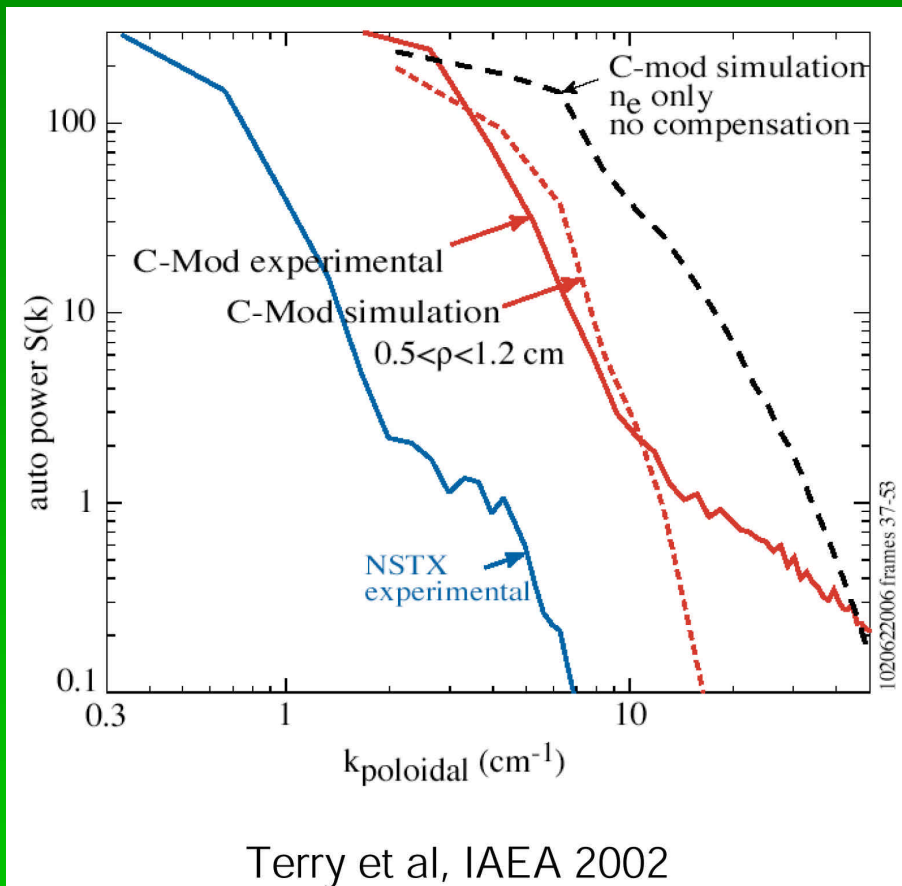
	C-Mod	NSTX
$B_T$	2–4 T	0.3–0.4 T
$L_c$	~5-10 mm	~40 mm
$t_c$	~10 ms	~40 ms

# Compare GPI Data with Simulations

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- 3-D nonlinear, drift-ballooning codes,
  - NLET « Non-Linear Electromagnetic Turbulence (Hallatschek, IPP-Garching)
  - BOUT « BOundary Turbulence (Xu, LLNL)
- Poloidal wavenumber spectra in rough agreement with observations.
- Dominant linear instability causing turbulence is resistive ballooning in both codes.

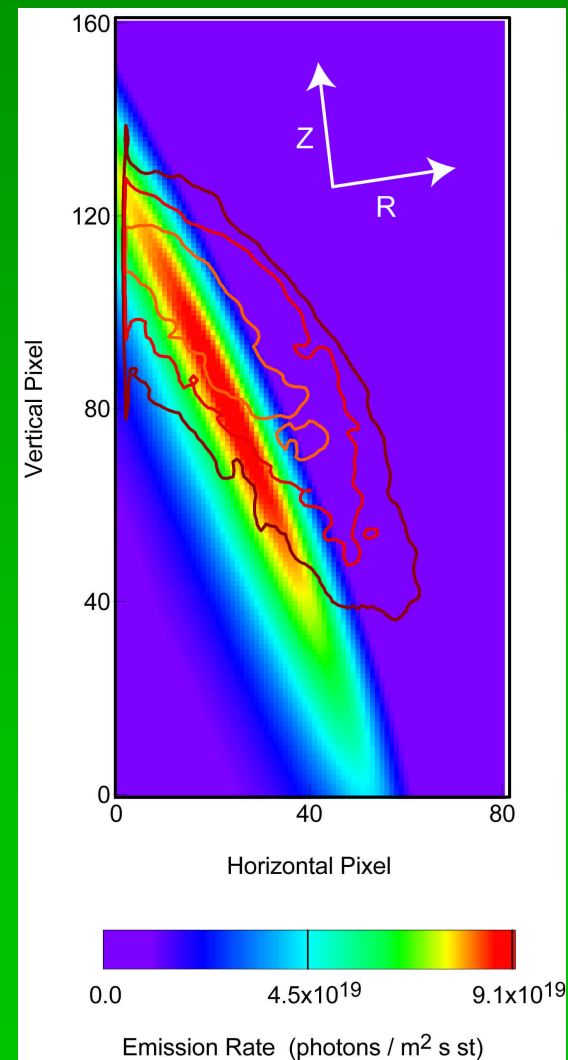
# Simulated & Observed $k_{pol}$ Spectra



NLET includes atomic physics function and spatial response of experimental optical system, suppressing small scale features

# DEGAS 2 Benchmark Against NSTX GPI

- 3-D DEGAS 2 with simulated camera view,
  - Steady state plasma with  $n_e$ ,  $T_e$  constant on flux surface.
- Simulated & observed clouds angled  $15^\circ$ ,
  - Simulation closely follows plasma contours,
  - GPI clouds not aligned with separatrix,
  - Generally, GPI cloud orientations vary  $20^\circ$ ,
    - But, equilibrium separatrix angles do not vary that much!
  - GPI hardware has not been moved
    - $\bar{P}$  can't blame calibration!
  - $\bar{P}$  Plasma parameters vary on flux surface and / or magnetic equilibrium not as predicted by EFIT !?!



# Inferring 2-D Time-Dependent $n_e$ & $T_e$ from GPI Data

J. Myra & D. D'Ippolito, Lodestar

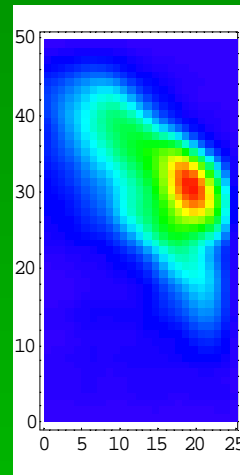
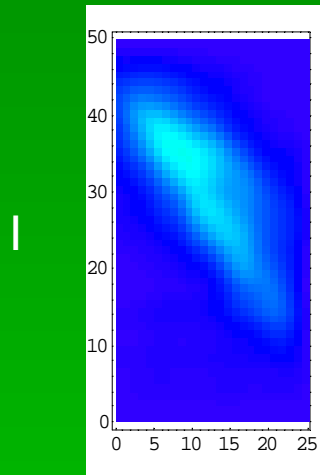
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- $I = n_0 F(n_e, T_e)$ ,
  - $F \ll$  atomic physics (known function),
  - Get  $n_0$  from DEGAS 2,
    - Assume  $n_0 = \text{constant}$  over turbulence timescale.
  - Experimental data  $\mathcal{P} I(x, y; t)$ ,
  - If know  $n_e(T_e)$ , can invert data to get 2-D  $n_e$ !
    - E.g., assume  $n_e$  &  $T_e$  passively convected together by  $\text{ExB}$  turbulent motion.
  - Use DEGAS 2 simulation based on Thomson scattering profile,
    - Calibrate against median GPI image  $\otimes$  shift & rotate  $n_0$  to match.
- Possible application:
  - Lodestar theory takes  $n_e(x, y)$  & computes  $F(x, y)$ ,
  - Use resulting  $\text{ExB}$  velocity to find blob shift,
  - Compare with next frame.

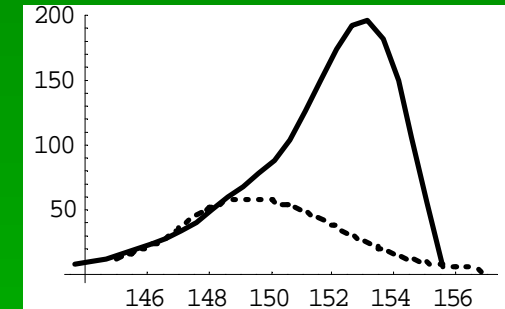
# Comparison of $n_e$ and $T_e$ for Equilibrium & Turbulent Frames

Equilibrium Frame

Bloppy Frame

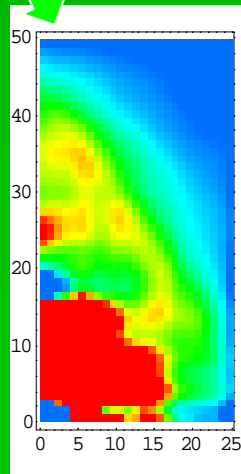
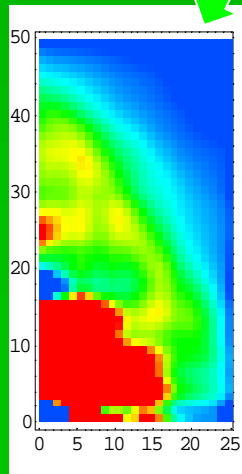


$I$



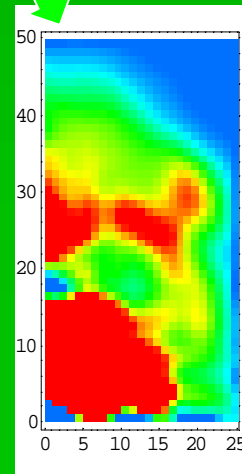
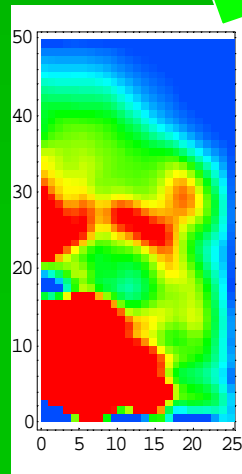
$n_e$

$T_e$

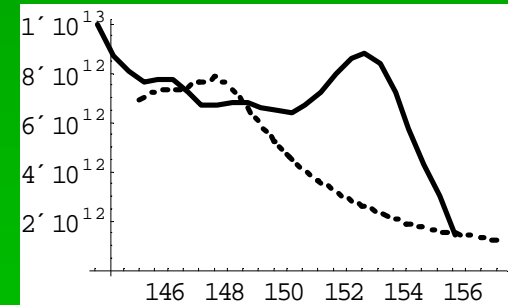


$n_e$

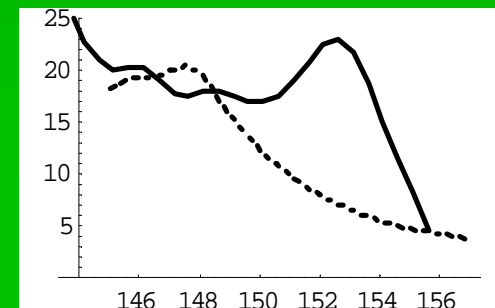
$T_e$



$n_e$

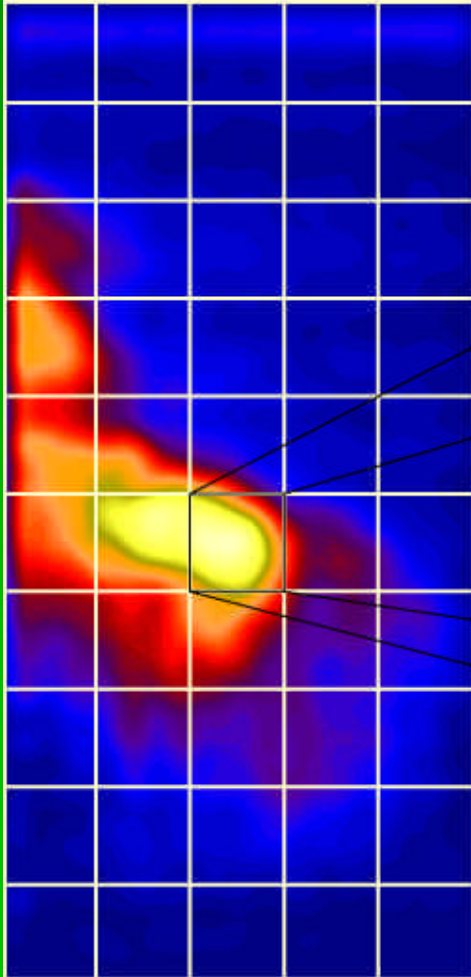


$T_e$

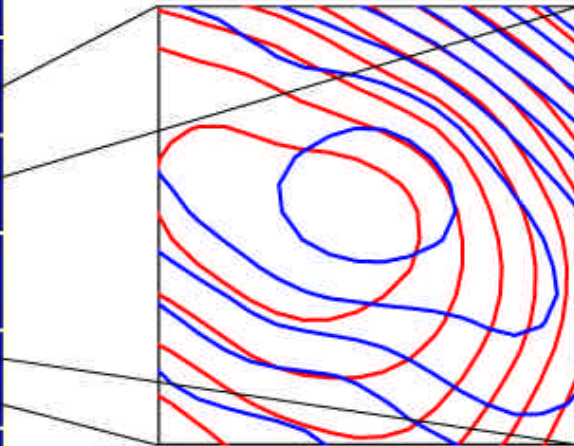


# Optical Flow Technique

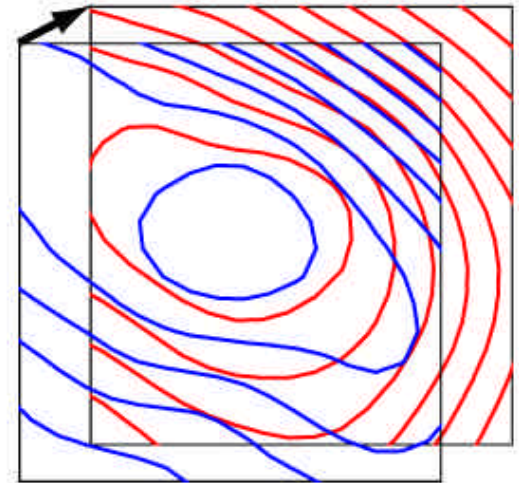
**Split image into tiles**



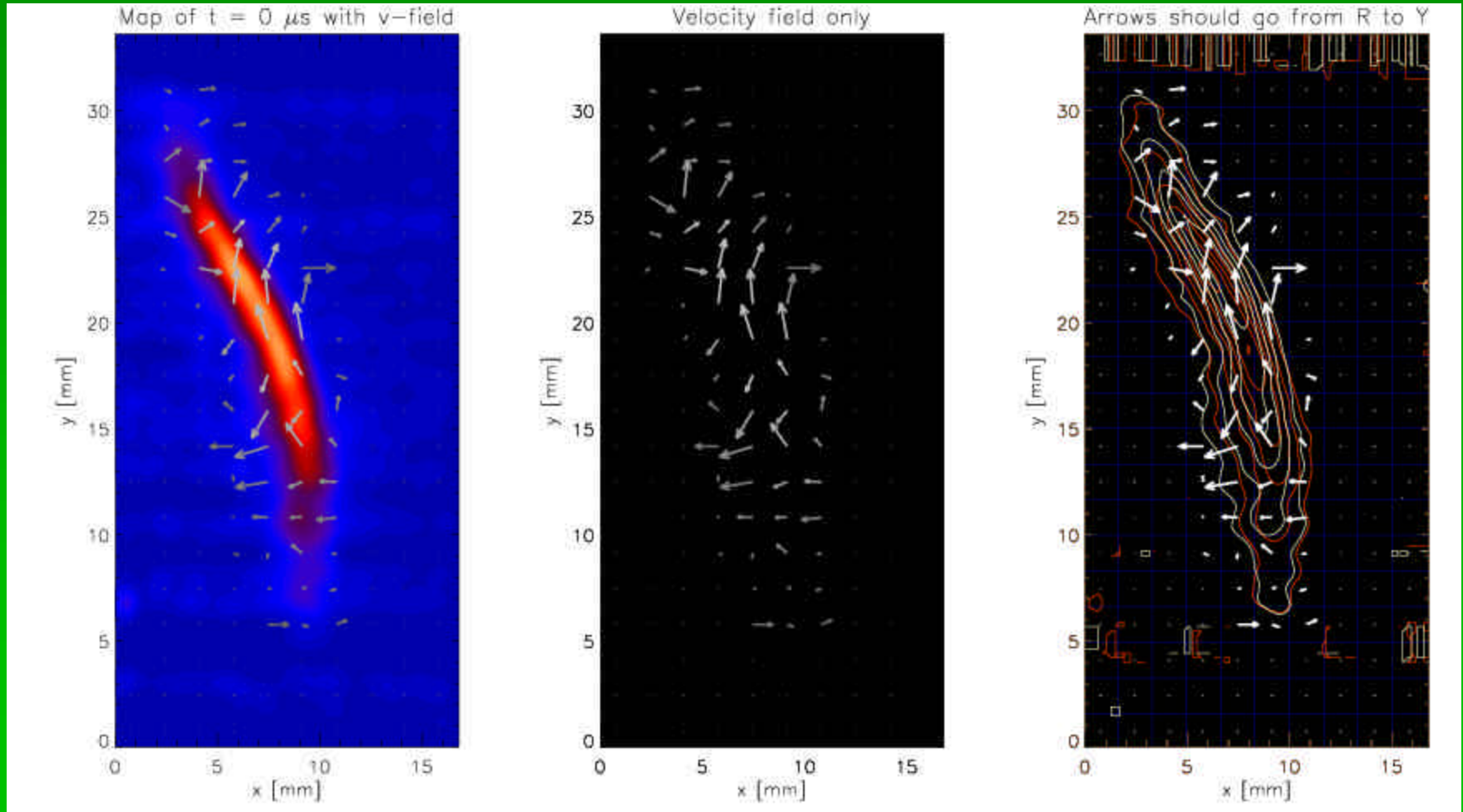
**Overlay each tile with  
tile from same location  
but next timepoint**



**Find offset that produces  
max cross-correlation  
to derive local  $\vec{v}(\vec{x}, t)$**

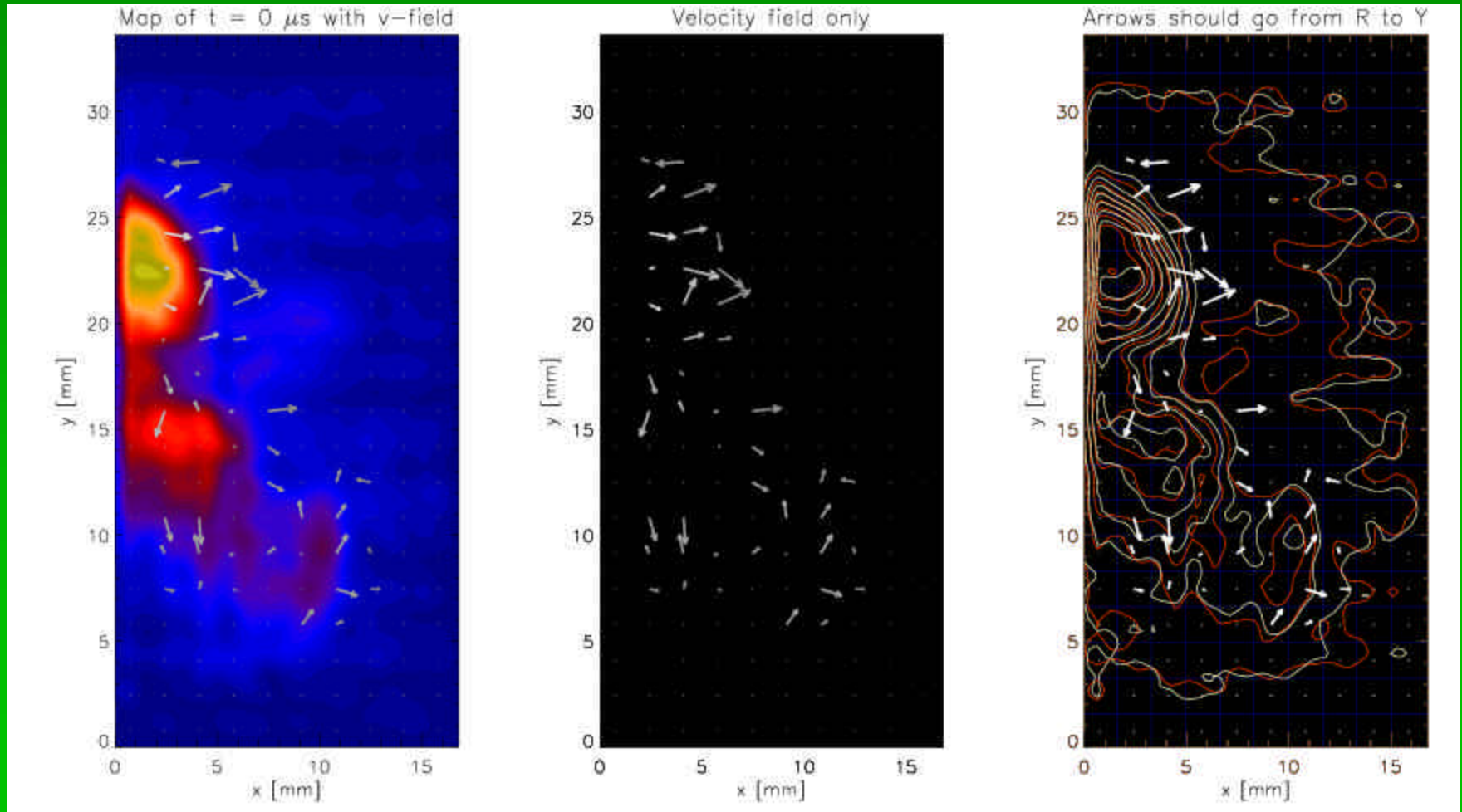


# Velocity Field – NSTX 108466





# Velocity Field – NSTX 108296



# Feature Tracking

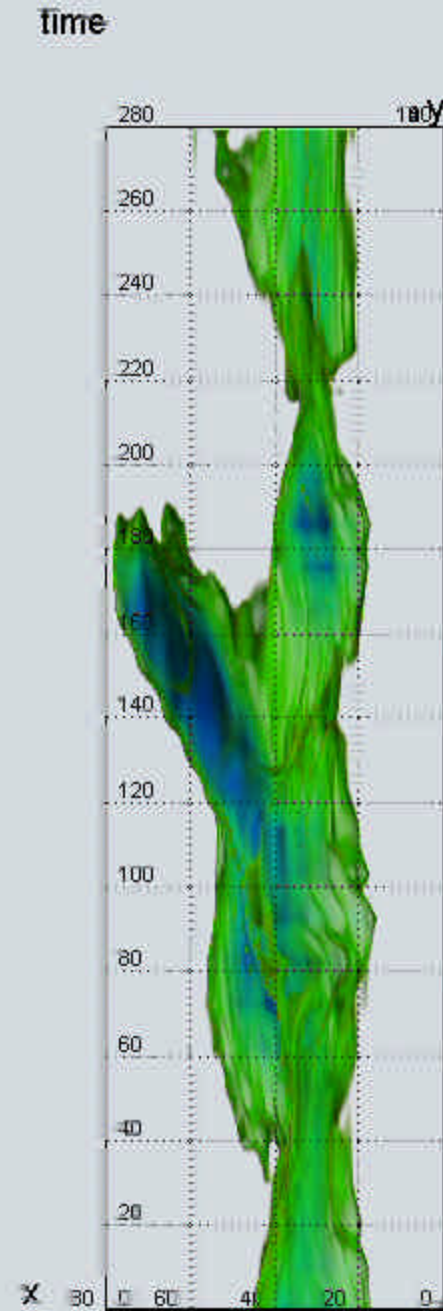
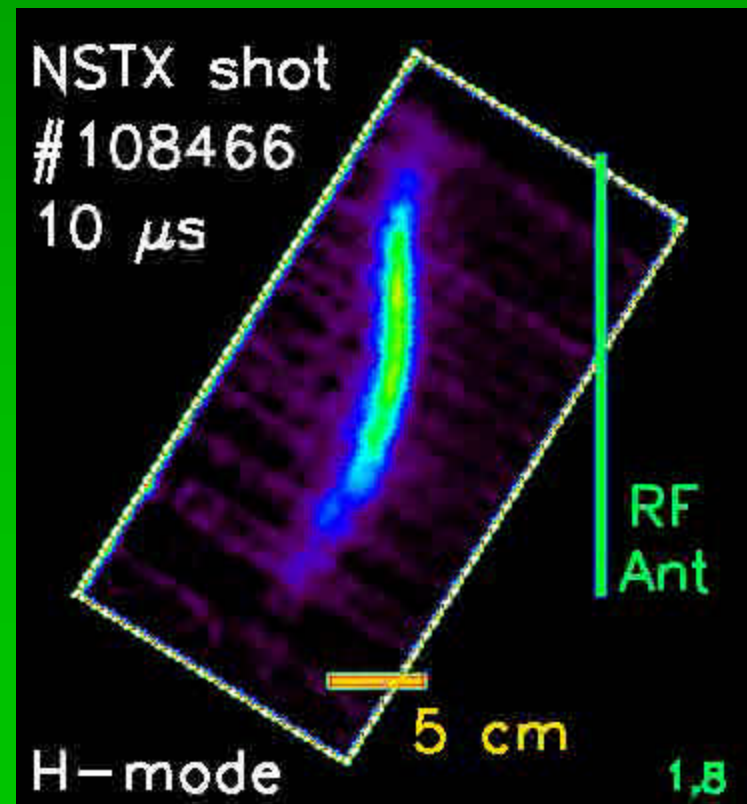
## D. Silver, Rutgers U.

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- Visualization software uses “thresholds” to identify & track objects in multidimensional datasets,
  - Has been applied in wide variety of areas.
- Yields number & size of blobs vs. time,
  - Another way to summarize large GPI data set for comparison with codes.
- We consider first 2-D vs. time GPI data as 3-D objects.

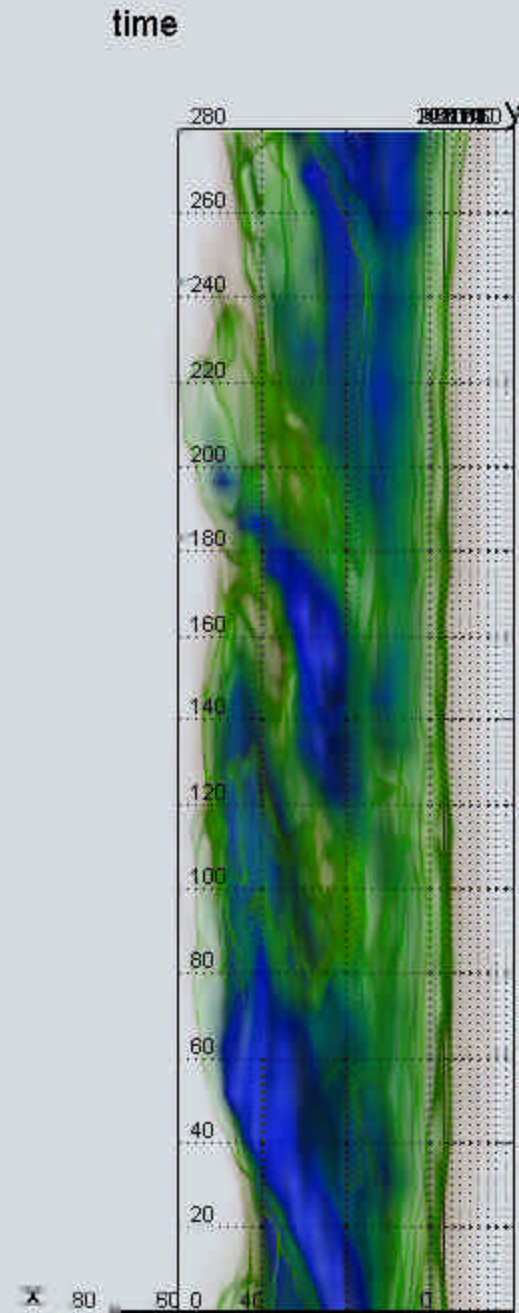
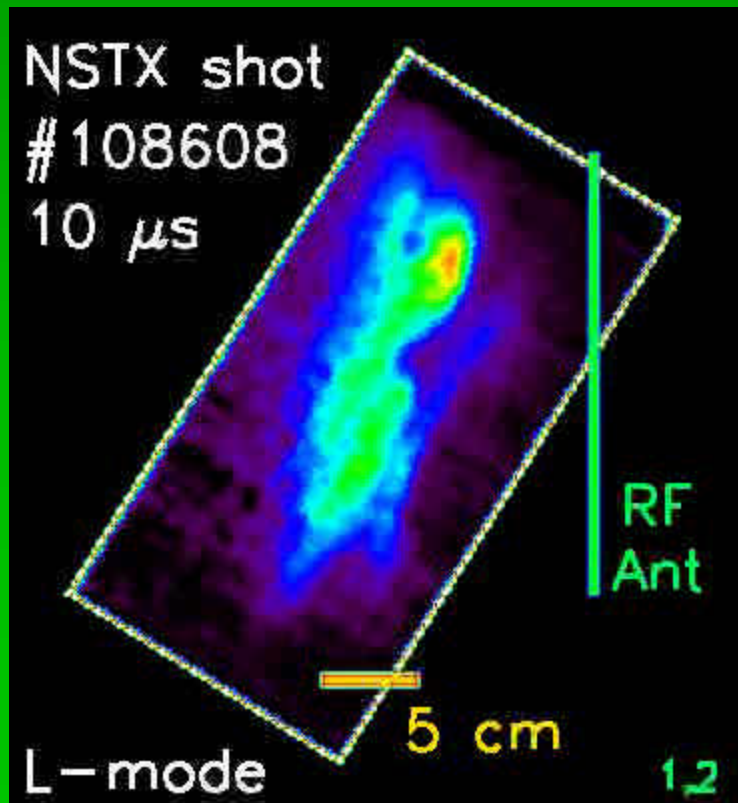
# Visualization by S. Klasky

- Time: vertical axis (10 ticks / frame)
- Horizontal plane  $\leftrightarrow$  80 x 160 camera image
- Volume rendering highlights two narrow bands near middle (green) and peak (blue) of data set.
- Moving slice replicates GPI frames with lower values in red.



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# Principal Component Analysis of GPI Data

## N. Pomphrey

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- PCA commonly used in geophysical sciences,
  - R.W. Presendorfer “Principal Component Analysis in Meteorology and Oceanography” (Elsevier, 1988)
- Seeks structures that explain the maximum amount of variance in a 2-D data (space vs. time).
- Structures in space dimension are “Empirical Orthogonal Functions” (EOF),
  - Accompanied by complementary structures in time dimension called “Principal Components” (PC).
- Both sets of structures are typically orthogonal, by construction, in their own dimension
  - This orthogonality constraint can be relaxed.

# Application to GPI

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- GPI data stored as 2-D matrix  $G(M,N)$ ,
  - $M$  = number of spatial points,
  - $N$  = number of time slices  $\ll M$ .
- Singular Value Decomposition of  $G = U S V^T$  is key to analysis,
  - Provides both EOF's & PC's.
  - Magnitudes of singular values of  $G$ , in diagonal matrix  $S$ , tell us fraction of variance within data set explained by each EOF spatial structure.
- Find that only small number ( $\sim 5$ ) of EOF's account for  $>90\%$  of variance in GPI data for a given shot.
- However, do the calculated dominant EOF's have any physical interpretation?
  - Orthogonality property of EOF's may be problematic here!
- Do dominant EOF's from shot-to-shot look the same?
- PCA analysis of GPI data is at an early stage of development!



# CONCLUSIONS

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- **Collected large amount of GPI data from C-Mod & NSTX under different conditions,**
  - Technique constantly being tweaked & improved.
- **Comparisons with probe data underway,**
  - See work by J. Boedo.
- **Simulations progressing,**
  - Results intriguing,
  - But, much remains to be done.
- **Analysis branching out,**
  - Hope to find new insight into nature of turbulence.

# References

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- Myra et al., APS 2003,
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